

Lepton Flavor Violating Decays of Neutral Higgses in Extended Mirror Fermion Model

Chia-Feng Chang ¹, Chia-Hung Vincent Chang ²,
Chrisna Setyo Nugroho ² and Tzu-Chiang Yuan ^{3,4}

¹*Department of Physics, National Taiwan University, Taipei 116, Taiwan*

²*Department of Physics, National Taiwan Normal University, Taipei 116, Taiwan*

³*Institute of Physics, Academia Sinica, Nangang, Taipei 11529, Taiwan*

⁴*Physics Division, National Center for Theoretical Sciences, Hsinchu, Taiwan*

(Dated: February 9, 2016)

Abstract

We perform the one-loop induced charged lepton flavor violating decays of the neutral Higgses in an extended mirror fermion model with non-sterile electroweak-scale right-handed neutrinos and a horizontal A_4 symmetry in the lepton sector. We demonstrate that for the 125 GeV scalar h there is tension between the recent LHC result $\mathcal{B}(h \rightarrow \tau\mu) \sim 1\%$ and the stringent limits on the rare processes $\mu \rightarrow e\gamma$ and $\tau \rightarrow (\mu \text{ or } e)\gamma$ from low energy experiments.

I. MOTIVATION

As is well known, lepton and baryon number are accidental global symmetries in the fundamental Lagrangian of Standard Model (SM). Processes like $\mu \rightarrow e\gamma$, $p \rightarrow e\gamma$, *etc* that violating either one (or both) of these two quantum numbers are thus strictly forbidden in the perturbation calculations of SM. Experimental limits for these processes are indeed very stringent. For example, from Particle Data Group [1], we have the following bounds

$$\mathcal{B}(\mu^- \rightarrow e^- \gamma) < 5.7 \times 10^{-13} \text{ (90 \% CL) } , \quad (1)$$

and

$$\tau(p \rightarrow e^+ \gamma) > 670 \times 10^{30} \text{ years} . \quad (2)$$

Search for lepton flavor violating (LFV) Higgs decay $h \rightarrow \tau\mu$ at hadron colliders was proposed some time ago [2]. Recently both ATLAS [3] and CMS [4] experiments at the Large Hadron Collider (LHC) have reported the following best fit branching ratios

$$\mathcal{B}(h \rightarrow \tau\mu) = \begin{cases} 0.84^{+0.39}_{-0.37} \% \text{ (2.4}\sigma\text{) [CMS] } , \\ 0.77 \pm 0.62 \% \text{ (1.2}\sigma\text{) [ATLAS] } . \end{cases} \quad (3)$$

However, at 95% confidence level (CL), the following upper limits can be deduced

$$\mathcal{B}(h \rightarrow \tau\mu) = \begin{cases} < 1.85 \% \text{ (95 \% CL) [ATLAS] } , \\ < 1.51 \% \text{ (95 \% CL) [CMS] } . \end{cases} \quad (4)$$

Despite low statistical significance the above best fit results in Eq. (3) are somewhat surprising since for a 125 GeV Higgs the branching ratio for this mode is about 3.6×10^{-6} in the SM augmented by the minuscule neutrino mass terms. A positive measurement of this branching ratio in the near future at the percent level would be a clear indication of new physics beyond the SM.

On the other hand, we have stringent limits for LFV radiative decays like $\mu \rightarrow e\gamma$ in Eq. (1) as well as

$$\mathcal{B}(\tau \rightarrow \mu\gamma) < 4.4 \times 10^{-8}, \quad (5)$$

$$\mathcal{B}(\tau \rightarrow e\gamma) < 3.3 \times 10^{-8}, \quad (6)$$

both at 90% CL from the low energy data of BaBar experiment [5].

Over the years, many authors had studied the flavor changing neutral current Higgs decays $h \rightarrow \bar{f}_i f_j$ in both the SM and its various extensions. For a recent updated calculation on $h \rightarrow \bar{q}_i q_j$ in the SM we refer the readers to [6] and references therein. For earlier calculations for the leptonic case with large Majorana neutrino masses, see for example [7, 8]. Recently large flux of works on new physics implications for the LHC result Eq. (3) is easily noticed [9–39].

In [40], an up-to-date analysis of a previous calculation [41] of $\mu \rightarrow e\gamma$ in a class of mirror fermion models with non-sterile electroweak scale right-handed neutrinos [42] was presented for an extension of the models with a horizontal A_4 symmetry in the lepton sector [43]. It was demonstrated in [40] that although there exists parameter space relevant to electroweak physics to accommodate the muon magnetic dipole moment anomaly $\Delta a_\mu = 288(63)(49) \times 10^{-11}$ [1], the current low energy limit Eq. (1) on the branching ratio $\mathcal{B}(\mu \rightarrow e\gamma)$ from MEG experiment [44] has disfavored those regions of parameter space.

In this work, we present the calculation of LFV decay of the neutral Higgses in an extended mirror fermion model. In Section 2, we briefly review the extended model and show the relevant interactions that may lead to the LFV decays of the neutral Higgses in the model. In Section 3, we present our calculation. Numerical results are given in Section 4. We conclude in Section 5. Detailed formulas for the loop amplitudes are given in the Appendix.

II. THE MODEL AND ITS RELEVANT INTERACTIONS

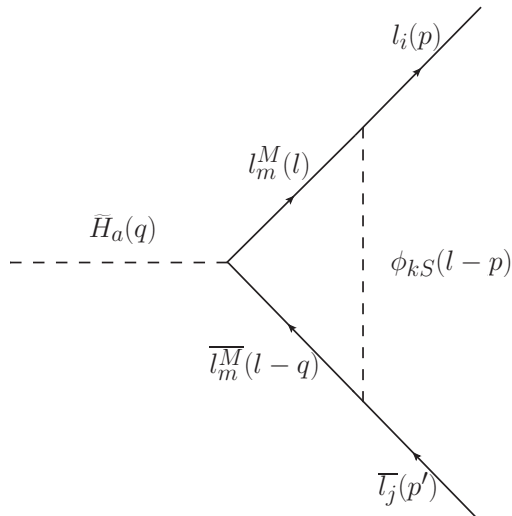


FIG. 1: One-loop induced Feynman diagram for $\tilde{H}_a(q) \rightarrow l_i(p) + \bar{l}_j(p')$ in EW-scale ν_R model. The other two 1-particle reducible diagrams corresponding to the wave function renormalization of the external fermion lines are not shown.

In the original mirror fermion model [42], while the gauge group is the same as SM, every left-handed (right-handed) SM fermion has a right-handed (left-handed) mirror partner, and the scalar sector consists of one SM Higgs doublet Φ , one singlet ϕ_{0S} and two triplets ξ and $\tilde{\chi}$ *à la* Georgi-Machacek [45, 46]. One peculiar feature of the model is that the right-handed neutrinos are non-sterile. They are paired up with right-handed mirror charged leptons to form electroweak doublets. This arrangement allows for the electroweak seesaw mechanism [42]: a small vacuum expectation value (VEV) of the scalar singlet ϕ_{0S} provides Dirac masses for the light neutrinos, while a VEV with electroweak size of the Georgi-Machacek triplets provide Majorana masses for the right-handed neutrinos.

Recently, the original model [42] is augmented with an additional mirror Higgs

doublet Φ_M in [47] so as to accommodate the 125 GeV Higgs observed at the LHC. In addition to the original singlet scalar ϕ_{0S} , a A_4 triplet of scalars $\{\phi_{kS}\}$ ($k = 1, 2, 3$) is introduced in [43] to implement a horizontal A_4 symmetry in the lepton sector which may lead to interesting lepton mixing effects. The three generations of SM leptons are assigned to be in a triplet of A_4 while the SM Higgs doublet and the triplets are singlets of A_4 .

We will consider both extensions with A_4 symmetry [43] and mirror Higgs doublet [47] in our calculation. The relevant Feynman diagram for LFV Higgs decay in the extended mirror model is one-loop induced and is shown in Fig. (1). The relevant interactions are all of Yukawa couplings. The first one is for the singlet ϕ_{0S} and triplet ϕ_{kS} ($k = 1, 2, 3$) [40]

$$\mathcal{L}_S = - \sum_{k=0}^3 \sum_{i,m=1}^3 (\bar{l}_{Li} \mathcal{U}_{im}^{Lk} l_{Rm}^M + \bar{l}_{Ri} \mathcal{U}_{im}^{Rk} l_{Lm}^M) \phi_{kS} + \text{H.c.} \quad (7)$$

where l_{Li} and l_{Ri} are SM leptons, l_{Rm}^M and l_{Lm}^M are mirror leptons (i, m are generation indices); \mathcal{U}_{im}^{Lk} and \mathcal{U}_{im}^{Rk} are the coupling coefficients given by

$$\begin{aligned} \mathcal{U}_{im}^{Lk} &\equiv \left(U_{\text{PMNS}}^\dagger \cdot M^k \cdot U_{\text{PMNS}}^M \right)_{im} , \\ &= \sum_{j,n=1}^3 \left(U_{\text{PMNS}}^\dagger \right)_{ij} M_{jn}^k (U_{\text{PMNS}}^M)_{nm} , \end{aligned} \quad (8)$$

$$\begin{aligned} \mathcal{U}_{im}^{Rk} &\equiv \left(U_{\text{PMNS}}'^\dagger \cdot M'^k \cdot U_{\text{PMNS}}'^M \right)_{im} , \\ &= \sum_{j,n=1}^3 \left(U_{\text{PMNS}}'^\dagger \right)_{ij} M_{jn}'^k (U_{\text{PMNS}}'^M)_{nm} , \end{aligned} \quad (9)$$

where the matrix elements for the four matrices M^k ($k = 0, 1, 2, 3$) are listed in Table I and $M_{jn}'^k$ can be obtained from M_{jn}^k with the following substitutions for the Yukawa couplings $g_{0S} \rightarrow g_{0S}'$ and $g_{1S} \rightarrow g_{1S}'$ [40]; U_{PMNS} is the usual neutrino mixing matrix defined as

$$U_{\text{PMNS}} = U_\nu^\dagger U_L^l , \quad (10)$$

and its mirror and right-handed counter-parts U_{PMNS}^M , U'_{PMNS} and U'^M_{PMNS} are defined analogously as

$$U_{\text{PMNS}}^M = U_\nu^\dagger U_R^M, \quad (11)$$

$$U'_{\text{PMNS}} = U_\nu^\dagger U_R^l, \quad (12)$$

and

$$U'^M_{\text{PMNS}} = U_\nu^\dagger U_L^M, \quad (13)$$

where U_R^l and U_L^M are the unitary matrices relating the gauge eigenstates (fields with superscripts 0) and the mass eigenstates

$$l_{L,R}^0 = U_{L,R}^l l_{L,R}, \quad l_{R,L}^{M,0} = U_{R,L}^M l_{R,L}^M, \quad (14)$$

and

$$U_\nu = U_L^\nu = U_R^\nu = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & \omega^2 & \omega \\ 1 & \omega & \omega^2 \end{pmatrix}, \quad (15)$$

where $\omega \equiv \exp(i2\pi/3)$ entered in the multiplication rules of A_4 . The matrix in Eq. (15) was first discussed by Cabibbo and also by Wolfenstein in the context of CP violation in three generations of neutrino oscillations [48].

The second Yukawa interaction is for the couplings of neutral Higgses with the SM fermion pairs and the mirror fermion pairs. It was shown in [47] that the physical neutral Higgs states $(\tilde{H}_1, \tilde{H}_2, \tilde{H}_3)$ ¹ are in general mixture of the unphysical neutral

¹ We note that $(\tilde{H}_1, \tilde{H}_2, \tilde{H}_3)$ was denoted as $(\tilde{H}, \tilde{H}', \tilde{H}'')$ respectively in [47].

TABLE I: Matrix elements for $M^k (k = 0, 1, 2, 3)$ where $\omega \equiv \exp(i2\pi/3)$ and g_{0S} and g_{1S} are Yukawa couplings.

M_{jn}^k	Value
$M_{12}^0, M_{13}^0, M_{21}^0, M_{23}^0, M_{31}^0, M_{32}^0$	0
$M_{11}^0, M_{22}^0, M_{33}^0$	g_{0S}
$M_{11}^1, M_{11}^2, M_{11}^3$	$\frac{2}{3}\text{Re}(g_{1S})$
$M_{22}^1, M_{22}^2, M_{22}^3$	$\frac{2}{3}\text{Re}(\omega^* g_{1S})$
$M_{33}^1, M_{33}^2, M_{33}^3$	$\frac{2}{3}\text{Re}(\omega g_{1S})$
M_{12}^1, M_{21}^1	$\frac{2}{3}\text{Re}(\omega g_{1S})$
M_{12}^2, M_{21}^3	$\frac{1}{3}(g_{1S} + \omega g_{1S}^*)$
M_{12}^3, M_{21}^2	$\frac{1}{3}(g_{1S}^* + \omega^* g_{1S})$
M_{13}^1, M_{31}^1	$\frac{2}{3}\text{Re}(\omega^* g_{1S})$
M_{13}^2, M_{31}^3	$\frac{1}{3}(g_{1S} + \omega^* g_{1S}^*)$
M_{13}^3, M_{31}^2	$\frac{1}{3}(g_{1S}^* + \omega g_{1S})$
M_{23}^1, M_{32}^1	$\frac{2}{3}\text{Re}(g_{1S})$
M_{23}^2, M_{32}^3	$\frac{2\omega^*}{3}\text{Re}(g_{1S})$
M_{23}^3, M_{32}^2	$\frac{2\omega}{3}\text{Re}(g_{1S})$

Higgs states $(H_1^0, H_{1M}^0, H_1^{0'})$ via an orthogonal transformation O [47]:

$$\begin{aligned}
\begin{pmatrix} \tilde{H}_1 \\ \tilde{H}_2 \\ \tilde{H}_3 \end{pmatrix} &= \begin{pmatrix} a_{1,1} & a_{1,1M} & a_{1,1'} \\ a_{1M,1} & a_{1M,1M} & a_{1M,1'} \\ a_{1',1} & a_{1',1M} & a_{1',1'} \end{pmatrix} \cdot \begin{pmatrix} H_1^0 \\ H_{1M}^0 \\ H_1^{0'} \end{pmatrix} \\
&\equiv O \cdot \begin{pmatrix} H_1^0 \\ H_{1M}^0 \\ H_1^{0'} \end{pmatrix}, \tag{16}
\end{aligned}$$

where H_1^0 and H_{1M}^0 are the neutral components of the SM Higgs and mirror Higgs doublets respectively, and $H_1^{0'}$ is linear combination of the neutral components in the Georgi-Machacek triplets. The couplings of the physical Higgs \tilde{H}_a with a pair of SM fermions f and a pair of mirror fermions f^M are given by [47]

$$\mathcal{L}_{\tilde{H}} = -\frac{g}{2m_W} \sum_{a,f} \tilde{H}_a \left\{ m_f \frac{O_{a1}}{s_2} \bar{f} f + m_{f^M} \frac{O_{a2}}{s_{2M}} \bar{f}^M f^M \right\}, \quad (17)$$

where g is the $SU(2)_L$ weak coupling constant; m_W is the W boson mass; O_{a1} and O_{a2} are the first and second columns of the above orthogonal matrix O in Eq. (16); s_2 , s_{2M} and s_M are mixing angles defined by

$$s_2 = \frac{v_2}{v}, \quad (18)$$

$$s_{2M} = \frac{v_{2M}}{v}, \quad (19)$$

$$s_M = \frac{2\sqrt{2}v_M}{v}, \quad (20)$$

with $v = \sqrt{v_2^2 + v_{2M}^2 + 8v_M^2} = 246$ GeV, where v_2 , v_{2M} and v_M are the VEVs of the Higgs doublet, mirror Higgs doublet and Georgi-Machacek triplets respectively. For the original mirror model [42], one can simply set $\tilde{H}_1 \rightarrow H_1^0 \equiv h$, O_{11}/s_2 and $O_{12}/s_{2M} \rightarrow 1$, and drop all other terms with $a \neq 1$ in Eq. (17).

III. THE CALCULATION

The matrix element for the process $\tilde{H}_a(q) \rightarrow l_i(p) + \bar{l}_j(p')$ (Fig. 1) can be written as

$$i\mathcal{M} = i \frac{1}{16\pi^2} \bar{u}_i(p) (C_L^{aij} P_L + C_R^{aij} P_R) v_j(p'), \quad (21)$$

where $P_{L,R} = (1 \mp \gamma_5)/2$ are the chiral projection operators. In terms of scalar and pseudoscalar couplings the above amplitude can be rewritten as

$$i\mathcal{M} = i \frac{1}{16\pi^2} \bar{u}_i(p) (A^{aij} + iB^{aij}\gamma_5) v_j(p'), \quad (22)$$

where

$$A^{ij} = \frac{1}{2} (C_L^{ij} + C_R^{ij}) \quad , \quad B^{ij} = \frac{1}{2i} (C_R^{ij} - C_L^{ij}) \quad . \quad (23)$$

The partial decay width is given by

$$\begin{aligned} \Gamma^{ij} = & \frac{1}{2^{11}\pi^5} m_{\tilde{H}_a} \lambda^{\frac{1}{2}} \left(1, \frac{m_i^2}{m_{\tilde{H}_a}^2}, \frac{m_j^2}{m_{\tilde{H}_a}^2} \right) \\ & \times \left[|A^{ij}|^2 \left(1 - \frac{(m_i + m_j)^2}{m_{\tilde{H}_a}^2} \right) + |B^{ij}|^2 \left(1 - \frac{(m_i - m_j)^2}{m_{\tilde{H}_a}^2} \right) \right] \quad , \quad (24) \end{aligned}$$

where $\lambda(x, y, z) = x^2 + y^2 + z^2 - 2(xy + yz + zx)$. The one-loop induced coefficients A^{ij} and B^{ij} are related to C_L^{ij} and C_R^{ij} according to Eq. (23). The formulas for the latter are given in the Appendix.

We now comment on the divergent cancellation in the calculation. For the original mirror model [42] in which there is only one Higgs doublet with Yukawa couplings to the SM fermions and to the mirror fermions that are differ only by the corresponding fermion masses, the divergence in the one-loop diagram in Fig. (1) will cancel with those in the two 1-particle reducible diagrams associated with wave function renormalization. On the other hand, for the extended model [47] these divergences do not cancel each other. Recall that in the extended model, besides the SM Higgs doublet an additional mirror Higgs doublet was introduced. Both Higgs doublets can then couple to the SM fermions and may lead to LFV decay of the Higgses at tree level. In [42], a global $U(1) \times U(1)$ symmetry was employed such that the SM Higgs doublet only couples to the SM fermions, while the mirror Higgs doublet only couples to the mirror fermions. Hence there will be no tree level LFV vertices for the SM Higgs decays into SM fermions. However this global symmetry is broken by a term in the scalar potential. This term also provide the Higgs mixings in Eq. (16) that eventually responsible to LFV decays of the Higgses in the extended model. Due to renormalizability, the presence of this symmetry breaking term in the scalar potential forces one to reintroduce the Yukawa terms that are forbidden by the symmetry.

Hence tree level LFV decays of the Higgses are generally present in the extended model. According to the general analysis in [39] such tree level LFV couplings are constrained to be quite small by low energy data. For our purpose, we will assume these tree level LFV couplings are vanishing small and the main reason for their existence is to provide counter terms to absorb the divergences in the calculation in the extended model. The results of $C_{L,R}^{aij}$ should then be regarded as renormalized quantities.

The amplitude for $l_i \rightarrow l_j \gamma$ in the extended model can be found in [40].

IV. NUMERICAL ANALYSIS

We will focus on the case of lightest neutral Higgs $\tilde{H}_1 \rightarrow \tau \mu$ with \tilde{H}_1 identified as the 125 GeV Higgs, and adopt the following strategy which has been used in [40] for the numerical analysis of $\mu \rightarrow e \gamma$:

- Two scenarios were specified according to the following forms of the three unknown mixing matrices:

Scenario 1 (S1): $U'_{\text{PMNS}} = U_{\text{PMNS}}^M = U_{\text{PMNS}}'^M = U_\nu = \text{Eq. (15)}$

Scenario 2 (S2): $U'_{\text{PMNS}} = U_{\text{PMNS}}^M = U_{\text{PMNS}}'^M = U_{\text{PMNS}}$, where

$$U_{\text{PMNS}}^{\text{NH}} = \begin{pmatrix} 0.8221 & 0.5484 & -0.0518 + 0.1439i \\ -0.3879 + 0.07915i & 0.6432 + 0.0528i & 0.6533 \\ 0.3992 + 0.08984i & -0.5283 + 0.05993i & 0.7415 \end{pmatrix}$$

and

$$U_{\text{PMNS}}^{\text{IH}} = \begin{pmatrix} 0.8218 & 0.5483 & -0.08708 + 0.1281i \\ -0.3608 + 0.0719i & 0.6467 + 0.04796i & 0.6664 \\ 0.4278 + 0.07869i & -0.5254 + 0.0525i & 0.7293 \end{pmatrix}$$

for the neutrino masses with normal and inverted hierarchies respectively. The Majorana phases have been ignored in the analyses. For each scenario, we consider these two possible solutions for the U_{PMNS} . Due to the small differences between these two solutions, we expect our results are not too sensitive to the neutrino mass hierarchies.

- All Yukawa couplings g_{0S}, g_{1S}, g'_{0S} and g'_{1S} are assumed to be real. For simplicity, we will assume $g_{0S} = g'_{0S}$, $g_{1S} = g'_{1S}$ and study the following 6 cases:
 - (a) $g_{0S} \neq 0$, $g_{1S} = 0$. The A_4 triplet terms are switched off.
 - (b) $g_{1S} = 10^{-2} \times g_{0S}$. The A_4 triplet couplings are merely one percent of the singlet ones.
 - (c) $g_{1S} = 10^{-1} \times g_{0S}$. The A_4 triplet couplings are 10 percent of the singlet ones.
 - (d) $g_{1S} = 0.5 \times g_{0S}$. The A_4 triplet couplings are one half of the singlet ones.
 - (e) $g_{1S} = g_{0S}$. Both A_4 singlet and triplet terms have the same weight.
 - (f) $g_{0S} = 0$, $g_{1S} \neq 0$. The A_4 singlet terms are switched off.
- For the masses of the singlet scalars ϕ_{kS} , we take

$$m_{\phi_{0S}} : m_{\phi_{1S}} : m_{\phi_{2S}} : m_{\phi_{3S}} = M_S : 2M_S : 3M_S : 4M_S$$

with a fixed common mass $M_S = 10$ MeV. As long as $m_{\phi_{kS}} \ll m_{l_m^M}$, our results will not be affected much by this assumption.

- For the masses of the mirror lepton l_m^M , we take

$$m_{l_m^M} = M_{\text{mirror}} + \delta_m$$

with $\delta_1 = 0$, $\delta_2 = 10$ GeV, $\delta_3 = 20$ GeV and vary the common mass M_{mirror} .

- As shown in [47], the 125 GeV scalar resonance h discovered at the LHC identified as the lightest state \tilde{H}_1 can be belonged to the *Dr. Jekyll* scenario in which the SM Higgs doublet H_1^0 has a major component or the *Mr. Hyde* scenario in which it is an impostor with H_1^0 only a sub-dominant component. Of all the explicit examples found for both of these scenarios, we will study the two following cases [47]:

- *Dr. Jekyll* case (Eq. (50) of [47]):

$$O = \begin{pmatrix} 0.998 & -0.0518 & -0.0329 \\ 0.0514 & 0.999 & -0.0140 \\ 0.0336 & 0.0123 & 0.999 \end{pmatrix}, \quad (25)$$

with $\text{Det}(O) = +1$, $m_{\tilde{H}_1} = 125.7$ GeV, $m_{\tilde{H}_2} = 420$ GeV, $m_{\tilde{H}_3} = 601$ GeV, $s_2 = 0.92$, $s_{2M} = 0.16$ and $s_M = 0.36$. In this case,

$$h \equiv \tilde{H}_1 \sim H_1^0, \quad \tilde{H}_2 \sim H_{1M}^0, \quad \tilde{H}_3 \sim H_1^{0'}. \quad (26)$$

Hence the 125 GeV Higgs identified as \tilde{H}_1 is composed mainly of the neutral component of the SM doublet in this scenario.

- *Mr. Hyde* case (Eq. (55) of [47]):

$$O = \begin{pmatrix} 0.187 & 0.115 & 0.976 \\ 0.922 & 0.321 & -0.215 \\ 0.338 & -0.940 & 0.046 \end{pmatrix}, \quad (27)$$

with $\text{Det}(O) = -1$, $m_{\tilde{H}_1} = 125.6$ GeV, $m_{\tilde{H}_2} = 454$ GeV, $m_{\tilde{H}_3} = 959$ GeV, $s_2 = 0.401$, $s_{2M} = 0.900$ and $s_M = 0.151$. In this case,

$$h \equiv \tilde{H}_1 \sim H_1^{0'}, \quad \tilde{H}_2 \sim H_1^0, \quad \tilde{H}_3 \sim H_{1M}^0. \quad (28)$$

Hence the 125 GeV Higgs identified as \tilde{H}_1 is an impostor in this scenario; it is mainly composed of the two neutral components in the Georgi-Machacek triplets.

In Fig. (2), we plot the contours of the branching ratios $\mathcal{B}(h \rightarrow \tau\mu) = 0.84\%$ (red), $\mathcal{B}(\mu \rightarrow e\gamma) = 5.7 \times 10^{-13}$ (black), $\mathcal{B}(\tau \rightarrow \mu\gamma) = 4.4 \times 10^{-8}$ (blue) and $\mathcal{B}(\tau \rightarrow e\gamma) = 3.3 \times 10^{-8}$ (green) on the $(\text{Log}_{10}(M_{\text{mirror}}), \text{Log}_{10}(g_{0S \text{ or } 1S}))$ plane for both Scenarios 1 and 2, normal and inverted mass hierarchies and the 6 different cases of the Yukawa couplings (Figs.(2a)-(2f)) in the *Dr. Jekyll* scenario as specified by Eqs. (25)-(26). For the four lines with the same color (hence same process), solid and dashed lines are for Scenario 1 and 2 with normal mass hierarchy (NH) respectively, while dotted and dot-dashed lines are for Scenario 1 and 2 with inverted mass hierarchy (IH) respectively.

Figs. (3a)-(3f) are the same as Figs. (2a)-(2f)) respectively but for *Mr. Hyde* scenario as specified by Eqs. (27)-(28).

By studying in details of all the plots in these two figures, we can deduce the following results:

- The bumps at $M_{\text{mirror}} \sim 200$ GeV at all the plots in these two figures are due to large cancellation in the amplitudes between the two one-particle reducible (wave function renormalization) diagrams and the irreducible one-loop diagram shown in Fig. (1). As a result, the Yukawa couplings have to be considerable larger in the contour lines of fixed branching ratios of the processes.

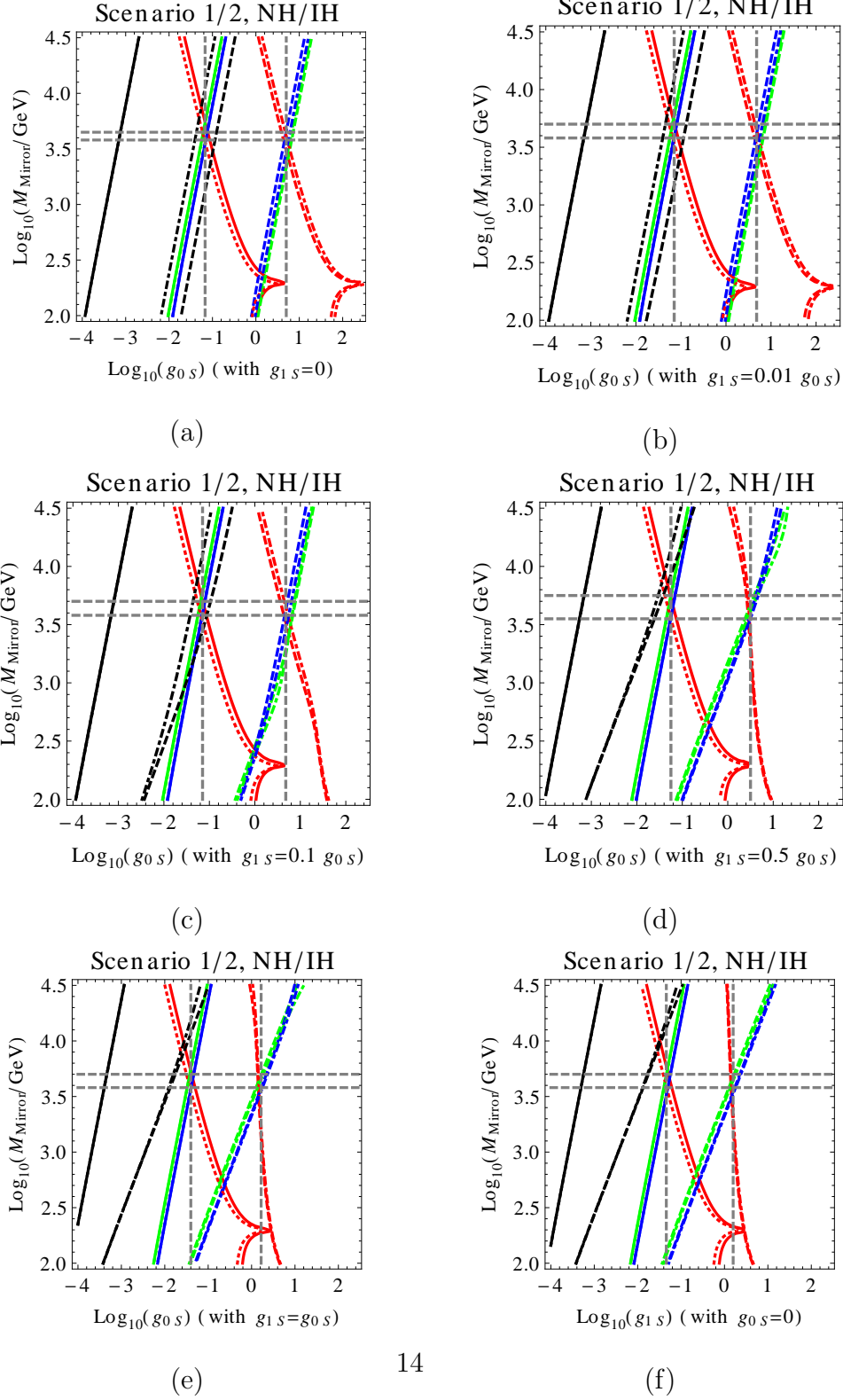


FIG. 2: Contour plots of $\mathcal{B}(h \rightarrow \tau\mu) = 0.84\%$ (red), $\mathcal{B}(\mu \rightarrow e\gamma) = 5.7 \times 10^{-13}$ (black), $\mathcal{B}(\tau \rightarrow \mu\gamma) = 4.4 \times 10^{-8}$ (blue) and $\mathcal{B}(\tau \rightarrow e\gamma) = 3.3 \times 10^{-8}$ (green) on the $(\text{Log}_{10}(M_{\text{mirror}}/\text{GeV}), \text{Log}_{10}(g_0 s \text{ or } 1s))$ plane for the *Dr. Jekyll* scenario. Solid: NH, S1; Dotted: IH, S1; Dashed: NH, S2; Dot-dashed: IH, S2. See text in Sec. IV for details.

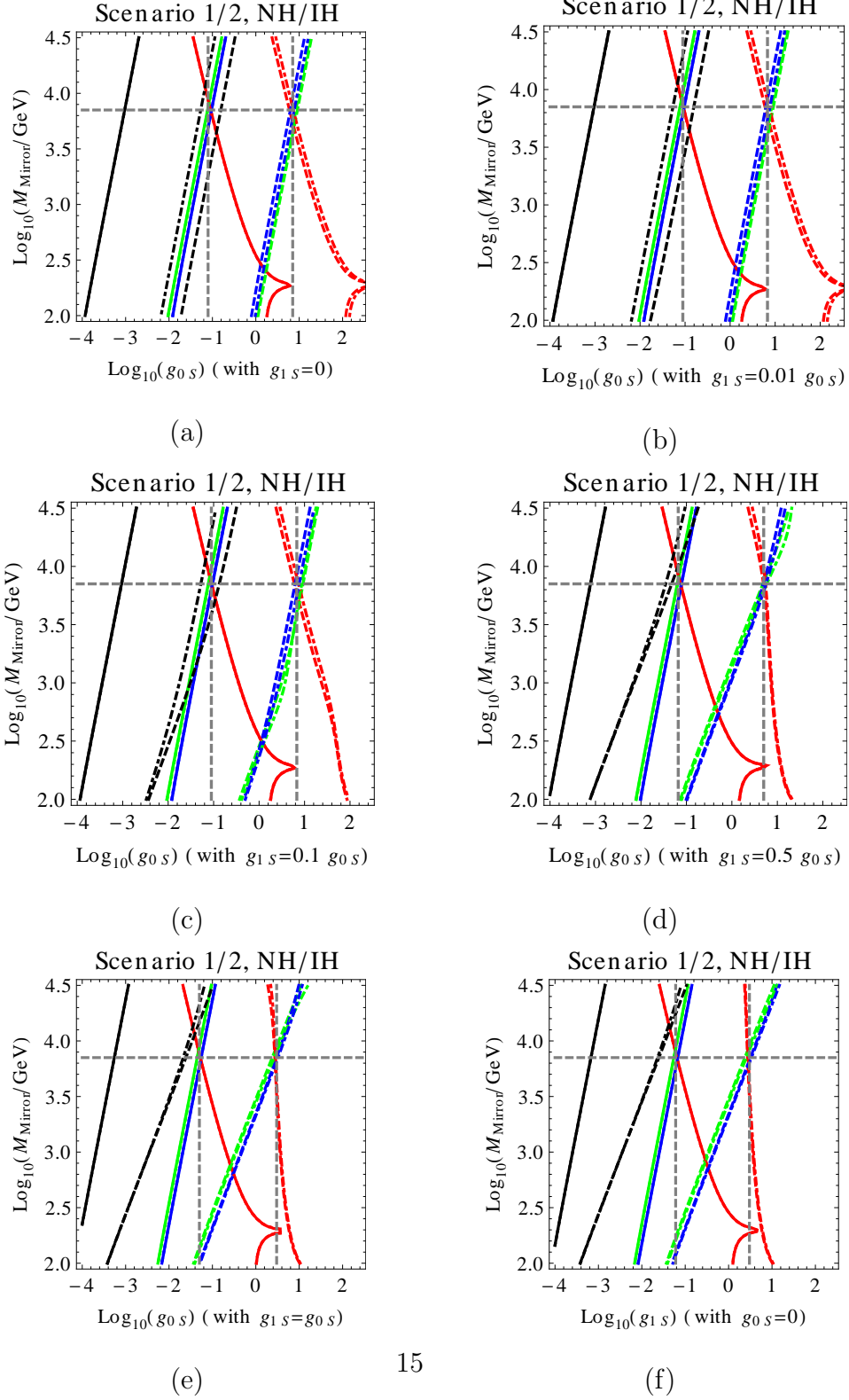


FIG. 3: Contour plots of $\mathcal{B}(h \rightarrow \tau\mu) = 0.84\%$ (red), $\mathcal{B}(\mu \rightarrow e\gamma) = 5.7 \times 10^{-13}$ (black), $\mathcal{B}(\tau \rightarrow \mu\gamma) = 4.4 \times 10^{-8}$ (blue) and $\mathcal{B}(\tau \rightarrow e\gamma) = 3.3 \times 10^{-8}$ (green) on the $(\text{Log}_{10}(M_{\text{mirror}}/\text{GeV}), \text{Log}_{10}(g_{0\text{ or }1}s))$ plane for the *Mr. Hyde* scenario. Solid: NH, S1; Dotted: IH, S1; Dashed: NH, S2; Dot-dashed: IH, S2. See text in Sec. IV for details.

- For the two processes $\tau \rightarrow \mu\gamma$ (blue lines) and $\tau \rightarrow e\gamma$ (green lines) in all these plots, the solid and dotted lines are coincide to each other while the dashed and dot-dashed lines are very close together. Thus there are essentially no differences between the normal and inverted mass hierarchies in both Scenarios 1 and 2 in these two processes. However, for the process $\mu \rightarrow e\gamma$ (black lines), only the solid and dotted lines are coincide to each other. Thus there are some differences between normal and inverted mass hierarchies in Scenario 2 but not in Scenario 1 for this process, in particular for cases (a)-(d) in which $g_{1S} \leq 0.5g_{0S}$.
- For $h \rightarrow \tau\mu$ (red lines), the solid (dashed) and dotted (dot-dashed) lines are either very close (in Fig. (2) for *Dr. Jekyll* scenario) or mostly coincide (in Fig. (3) for *Mr. Hyde* scenario).
- Note that the regions to the right side of the black, blue and green lines in all the plots in these two figures are excluded by the low energy limits of $\mathcal{B}(\mu \rightarrow e\gamma)$, $\mathcal{B}(\tau \rightarrow \mu\gamma)$ and $\mathcal{B}(\tau \rightarrow e\gamma)$ respectively. The CMS result of $\mathcal{B}(h \rightarrow \tau\mu) = 0.84\%$ (red lines), if not due to statistical fluctuations, is compatible with these low energy limits only if there are intersection points of the red lines with the corresponding black, blue and green lines.

Take Fig. (2a) as an example. For case of *Dr. Jekyll* and in Scenario 1, the solid (or dotted) red line intersects with the solid (or dotted) blue and green lines at $M_{\text{mirror}} \sim 4.47$ TeV where $g_{0S} \sim 0.0676$. In Scenario 2, the dashed (or dot-dashed) red line intersects the dashed (or dot-dashed) blue or green lines at $M_{\text{mirror}} \sim 3.55$ TeV with a considerable larger $g_{0S} \sim 5.01$. For the black lines from the most stringent limit of $\mu \rightarrow e\gamma$, their intersections with the red lines are well beyond 10 TeV for the mirror lepton masses. Similar statements can be obtained from the other plots in these two figures. From

TABLE II: The lower (upper) limit of mirror fermion masses (couplings).

Mode	Quantity	Scenario 1		Scenario 2	
		<i>Dr. Jekyll</i>	<i>Mr. Hyde</i>	<i>Dr. Jekyll</i>	<i>Mr. Hyde</i>
$\tau \rightarrow (\mu, e)\gamma$	Mass (TeV)	4.47	7.08	3.55	7.08
	$g_{0S}(g_{1S})$	0.07	0.09	5.01	6.76
$\mu \rightarrow e\gamma$	Mass (TeV)	~ 100	$> 10^{2.5}$	~ 95	$> 10^{2.5}$
	$g_{0S}(g_{1S})$	$10^{-2.6}$	$10^{-2.1}$	0.16	0.40

these intersections in these figures, one can deduce the lower (upper) limits of the mirror fermion masses (couplings) which we summarize in Table II. Such a large mirror lepton mass M_{mirror} or coupling g_{0S} indicates a break down of the perturbative calculation and/or violation of unitarity. However taking what we have literally there is tension between the large branching ratio $\mathcal{B}(h \rightarrow \tau\mu)$ from LHC and the low energy limits of $\mathcal{B}(\tau \rightarrow (\mu, e)\gamma)$ and $\mathcal{B}(\mu \rightarrow e\gamma)$, in particular the latter one.

- In the event that the CMS result in Eq. (3) is just a statistical fluctuation, the limits in Eq. (4) will be improved further in LHC Run 2. The contour lines of these future limits would be located to the left side of the current red lines in the two Figs. (2) and (3). Their intersections with the black, blue and green lines would then be at lower mirror lepton masses and smaller Yukawa couplings, since the low energy limits of the LFV decays $l_i \rightarrow l_j\gamma$ are unlikely to be changed significantly anytime soon. Certainly this would alleviate the tension mentioned above.

V. CONCLUSION

To summarize, CMS has reported excess in the charged lepton flavor violating Higgs decay $h \rightarrow \tau\mu$ at 2.4σ level. More data is needed to collect at Run 2 so as to confirm whether these are indeed true signals or simply statistical fluctuations.

If the branching ratio of $h \rightarrow \tau\mu$ is indeed at the percent level, new physics associated with lepton flavor violation may be at a scale not too far from the electroweak scale. Crucial question is whether this large branching ratio of $h \rightarrow \tau\mu$ is compatible with the current low energy limits of $\tau \rightarrow \mu\gamma$ and $\tau \rightarrow e\gamma$ from Belle experiments and the most stringent limit of $\mu \rightarrow \gamma$ from MEG experiment.

We analyze these lepton flavor violating processes in the context of an extended mirror fermion model with non-sterile electroweak scale right-handed neutrinos as well as a horizontal A_4 symmetry imposed on the lepton sector. We found that the masses of the mirror lepton fermions entering the loops of these processes can be of the order of a few hundred GeV to a few TeV depending on the sizes of the Yukawa couplings among the leptons, mirror leptons and the scalar singlets in the model as well as whether or not the 125 GeV scalar boson is a Higgs impostor and which scenario one assumes for the three unknown PMNS-type mixing matrices. We demonstrate that in general there is tension between the LHC result and the low energy limits since these results are compatible only if the mirror lepton masses are quite heavy and/or the Yukawa couplings involving the scalar singlets are large.

Before we depart, we comment on the possible collider signals for the mirror fermions [49]. Mirror leptons if not too heavy can be produced at the LHC via electroweak processes [42], *e.g.* $q\bar{q} \rightarrow Z \rightarrow l_R^M \bar{l}_R^M, \nu_R \bar{\nu}_R$ and $q\bar{q}' \rightarrow W^\mp \rightarrow l_R^M \bar{\nu}_R, \nu_R \bar{l}_R^M$. The mirror lepton decays as $l_R^M \rightarrow l_L + \phi_S$ or $l_R^M \rightarrow \nu_R + W^{-(*)}$ for $m_{l_R^M} > m_{\nu_R}$ plus the conjugate processes, while the right-handed neutrino can decay as $\nu_R \rightarrow \nu_L + \phi_S$ or $\nu_R \rightarrow l_R^M + W^{+(*)}$ for $m_{\nu_R} > m_{l_R^M}$ followed by $l_R^M \rightarrow l_L + \phi_S$. If kinematics allowed,

the scalar singlet ϕ_S can decay into lepton pair as well through mixings; otherwise they would appear as missing energies like neutrinos. Thus the signals at the LHC or future 100 TeV SPPC would be multiple lepton pairs plus missing energies. In the case where the right-handed neutrinos are Majorana fermions, we would have same sign dilepton plus missing energies. Assuming $l_R^M \rightarrow l_L + \phi_S$ is the dominant mode and the Yukawa couplings are small enough, the decay length of the mirror lepton could be as large as a few millimeter [49]. Thus the mirror lepton may lead to a displaced vertex and decay outside the beam pipe. These leptonic final states may have been discarded by the current algorithms adopted by the LHC experiments. It is therefore quite important for the experimentalists to devise new algorithms to search for these mirror fermions that may decay outside the beam pipe.

The scale of new physics may be hidden in the lepton flavor violating processes like $h \rightarrow \tau(\mu, e)$, $\tau \rightarrow (\mu, e)\gamma$, $\mu \rightarrow e\gamma$, $\mu \rightarrow eee$, μ - e conversion *etc.* Ongoing and future experiments at high energy and high intensity frontiers could shed light in the mirror fermion model that may responsible to these lepton flavor violating processes.

ACKNOWLEDGMENTS

We would like to thank P. Q. Hung for useful discussions. This work was supported in part by the Ministry of Science and Technology (MoST) of Taiwan under grant numbers 104-2112-M-001-001-MY3.

APPENDIX

The dimensionless coefficients C_L^{aij} and C_R^{aij} defined in Eq. (22) are given by

$$\begin{aligned}
C_L^{aij} = & \frac{gO_{a1}}{2s_2m_W(m_i^2 - m_j^2)} \sum_{k,m} \int_0^1 dx \left\{ \left[(1-x) \left(m_i m_j^2 \mathcal{U}_{im}^{Lk} (\mathcal{U}_{mj}^{Lk})^* + m_j m_i^2 \mathcal{U}_{im}^{Rk} (\mathcal{U}_{mj}^{Rk})^* \right) \right. \right. \\
& + \left. m_i m_j M_m \mathcal{U}_{im}^{Lk} (\mathcal{U}_{mj}^{Rk})^* \right] \log \left(\frac{\Delta_1}{\Delta_2} \right) + M_m \mathcal{U}_{im}^{Rk} (\mathcal{U}_{mj}^{Lk})^* (m_i^2 \log \Delta_1 - m_j^2 \log \Delta_2) \Big\} \\
& + \frac{gO_{a2}}{2s_{2M}m_W} \sum_{k,m} M_m \mathcal{U}_{im}^{Rk} (\mathcal{U}_{mj}^{Lk})^* \left(-\frac{1}{2} - 2 \int_0^1 dx \int_0^{1-x} dy \log \Delta_3 \right) \\
& - \frac{gO_{a2}}{2s_{2M}m_W} \sum_{k,m} M_m \int_0^1 dx \int_0^{1-x} dy \frac{1}{\Delta_3} \left\{ (1-2y) \frac{m_i M_m}{m_{\tilde{H}_a}^2} \mathcal{U}_{im}^{Lk} (\mathcal{U}_{mj}^{Lk})^* \right. \\
& + (1-2x) \frac{m_j M_m}{m_{\tilde{H}_a}^2} \mathcal{U}_{im}^{Rk} (\mathcal{U}_{mj}^{Rk})^* + (1-x-y) \frac{m_i m_j}{m_{\tilde{H}_a}^2} \mathcal{U}_{im}^{Lk} (\mathcal{U}_{mj}^{Rk})^* \\
& \left. - [xy + (1-x-y)(yr_i + xr_j) - r_m] \mathcal{U}_{im}^{Rk} (\mathcal{U}_{mj}^{Lk})^* \right\}, \tag{29}
\end{aligned}$$

C_R^{aij} can be obtained from C_L^{aij} simply by substituting $\mathcal{U}^L \leftrightarrow \mathcal{U}^R$, namely

$$\begin{aligned}
C_R^{aij} = & \frac{gO_{a1}}{2s_2m_W(m_i^2 - m_j^2)} \sum_{k,m} \int_0^1 dx \left\{ \left[(1-x) \left(m_i m_j^2 \mathcal{U}_{im}^{Rk} (\mathcal{U}_{mj}^{Rk})^* + m_j m_i^2 \mathcal{U}_{im}^{Lk} (\mathcal{U}_{mj}^{Lk})^* \right) \right. \right. \\
& + \left. m_i m_j M_m \mathcal{U}_{im}^{Rk} (\mathcal{U}_{mj}^{Lk})^* \right] \log \left(\frac{\Delta_1}{\Delta_2} \right) + M_m \mathcal{U}_{im}^{Lk} (\mathcal{U}_{mj}^{Rk})^* (m_i^2 \log \Delta_1 - m_j^2 \log \Delta_2) \Big\} \\
& + \frac{gO_{a2}}{2s_{2M}m_W} \sum_{k,m} M_m \mathcal{U}_{im}^{Lk} (\mathcal{U}_{mj}^{Rk})^* \left(-\frac{1}{2} - 2 \int_0^1 dx \int_0^{1-x} dy \log \Delta_3 \right) \\
& - \frac{gO_{a2}}{2s_{2M}m_W} \sum_{k,m} M_m \int_0^1 dx \int_0^{1-x} dy \frac{1}{\Delta_3} \left\{ (1-2y) \frac{m_i M_m}{m_{\tilde{H}_a}^2} \mathcal{U}_{im}^{Rk} (\mathcal{U}_{mj}^{Rk})^* \right. \\
& + (1-2x) \frac{m_j M_m}{m_{\tilde{H}_a}^2} \mathcal{U}_{im}^{Lk} (\mathcal{U}_{mj}^{Lk})^* + (1-x-y) \frac{m_i m_j}{m_{\tilde{H}_a}^2} \mathcal{U}_{im}^{Rk} (\mathcal{U}_{mj}^{Lk})^* \\
& \left. - [xy + (1-x-y)(yr_i + xr_j) - r_m] \mathcal{U}_{im}^{Lk} (\mathcal{U}_{mj}^{Rk})^* \right\}. \tag{30}
\end{aligned}$$

The Δ_1 , Δ_2 and Δ_3 are given by

$$\Delta_1 = xr_m + (1-x)r_k - x(1-x)r_j - i0^+, \quad (31)$$

$$\Delta_2 = xr_m + (1-x)r_k - x(1-x)r_i - i0^+, \quad (32)$$

$$\Delta_3 = (x+y)r_m + (1-x-y)(r_k - yr_i - xr_j) - xy - i0^+. \quad (33)$$

Here $r_m = M_m^2/m_{\tilde{H}_a}^2$, $r_{i,j} = m_{i,j}^2/m_{\tilde{H}_a}^2$ and $r_k = m_k^2/m_{\tilde{H}_a}^2$ with M_m , $m_{i,j}$ and m_k denoting the masses of the mirror leptons, leptons and scalar singlets respectively.

-
- [1] K. A. Olive *et al.* (Particle Data Group), Chin. Phys. C, **38**, 090001 (2014) and (2015) update.
 - [2] T. Han and D. Marfatia, Phys. Rev. Lett. **86**, 1442 (2001) [hep-ph/0008141].
 - [3] G. Aad *et al.* [ATLAS Collaboration], arXiv:1508.03372 [hep-ex].
 - [4] V. Khachatryan *et al.* [CMS Collaboration], Phys. Lett. B **749**, 337 (2015) [arXiv:1502.07400 [hep-ex]].
 - [5] B. Aubert *et al.* [BaBar Collaboration], Phys. Rev. Lett. **104**, 021802 (2010) [arXiv:0908.2381 [hep-ex]].
 - [6] L. G. Benitez-Guzmán, I. García-Jiménez, M. A. López-Osorio, E. Martínez-Pascual and J. J. Toscano, J. Phys. G **42**, 085002 (2015) [arXiv:1506.02718 [hep-ph]].
 - [7] A. Pilaftsis, Phys. Lett. B **285**, 68 (1992).
 - [8] J. G. Korner, A. Pilaftsis and K. Schilcher, Phys. Rev. D **47**, 1080 (1993) [hep-ph/9301289].
 - [9] I. Doršner, S. Fajfer, A. Greljo, J. F. Kamenik, N. Košnik and I. Nišandžić, JHEP **1506**, 108 (2015) [arXiv:1502.07784 [hep-ph]].
 - [10] X. F. Han, L. Wang and J. M. Yang, arXiv:1601.04954 [hep-ph].
 - [11] M. Sher and K. Thrasher, arXiv:1601.03973 [hep-ph].

- [12] M. Buschmann, J. Kopp, J. Liu and X. P. Wang, arXiv:1601.02616 [hep-ph].
- [13] A. Crivellin, G. D'Ambrosio, M. Hoferichter and L. C. Tunstall, arXiv:1601.00970 [hep-ph]; A. Crivellin, J. Heeck and P. Stoffer, arXiv:1507.07567 [hep-ph]; A. Crivellin, G. D'Ambrosio and J. Heeck, Phys. Rev. D **91**, no. 7, 075006 (2015) [arXiv:1503.03477 [hep-ph]]; A. Crivellin, G. D'Ambrosio and J. Heeck, Phys. Rev. Lett. **114**, 151801 (2015) [arXiv:1501.00993 [hep-ph]].
- [14] N. Bizot, S. Davidson, M. Frigerio and J.-L. Kneur, arXiv:1512.08508 [hep-ph].
- [15] L. T. Hue, H. N. Long, T. T. Thuc and N. T. Phong, arXiv:1512.03266 [hep-ph].
- [16] J. M. Cline, arXiv:1512.02210 [hep-ph].
- [17] H. B. Zhang, T. F. Feng, S. M. Zhao, Y. L. Yan and F. Sun, arXiv:1511.08979 [hep-ph].
- [18] Y. Omura, E. Senaha and K. Tobe, arXiv:1511.08880 [hep-ph].
- [19] R. Benbrik, C. H. Chen and T. Nomura, arXiv:1511.08544 [hep-ph].
- [20] D. Aloni, Y. Nir and E. Stamou, arXiv:1511.00979 [hep-ph].
- [21] E. Arganda, M. J. Herrero, R. Morales and A. Szyrkman, arXiv:1510.04685 [hep-ph].
- [22] Y. Cai and M. A. Schmidt, arXiv:1510.02486 [hep-ph].
- [23] S. Baek and Z. F. Kang, arXiv:1510.00100 [hep-ph].
- [24] X. Chen and L. Xia, arXiv:1509.08149 [hep-ph].
- [25] S. Baek and K. Nishiwaki, Phys. Rev. D **93**, no. 1, 015002 (2016) [arXiv:1509.07410 [hep-ph]].
- [26] N. Košnik, arXiv:1509.04590 [hep-ph].
- [27] X. Liu, L. Bian, X. Q. Li and J. Shu, arXiv:1508.05716 [hep-ph].
- [28] F. J. Botella, G. C. Branco, M. Nebot and M. N. Rebelo, arXiv:1508.05101 [hep-ph].
- [29] E. Arganda, M. J. Herrero, X. Marcano and C. Weiland, arXiv:1508.04623 [hep-ph].
- [30] Y. n. Mao and S. h. Zhu, arXiv:1505.07668 [hep-ph].
- [31] B. Altunkaynak, W. S. Hou, C. Kao, M. Kohda and B. McCoy, Phys. Lett. B **751**, 135 (2015) [arXiv:1506.00651 [hep-ph]].

- [32] X. G. He, J. Tandean and Y. J. Zheng, JHEP **1509**, 093 (2015) [arXiv:1507.02673 [hep-ph]].
- [33] C. W. Chiang, H. Fukuda, M. Takeuchi and T. T. Yanagida, JHEP **1511**, 057 (2015) [arXiv:1507.04354 [hep-ph]].
- [34] W. Altmannshofer, S. Gori, A. L. Kagan, L. Silvestrini and J. Zupan, arXiv:1507.07927 [hep-ph].
- [35] K. Cheung, W. Y. Keung and P. Y. Tseng, Phys. Rev. D **93**, no. 1, 015010 (2016) [arXiv:1508.01897 [hep-ph]].
- [36] D. Das and A. Kundu, Phys. Rev. D **92**, no. 1, 015009 (2015) [arXiv:1504.01125 [hep-ph]].
- [37] J. Heeck, M. Holthausen, W. Rodejohann and Y. Shimizu, Nucl. Phys. B **896**, 281 (2015) [arXiv:1412.3671 [hep-ph]].
- [38] D. Aristizabal Sierra and A. Vicente, Phys. Rev. D **90**, no. 11, 115004 (2014) [arXiv:1409.7690 [hep-ph]].
- [39] R. Harnik, J. Kopp and J. Zupan, JHEP **1303**, 026 (2013) [arXiv:1209.1397 [hep-ph]].
- [40] P. Q. Hung, T. Le, V. Q. Tran and T. C. Yuan, JHEP **1512**, 169 (2015) [arXiv:1508.07016 [hep-ph]].
- [41] P. Q. Hung, Phys. Lett. B **659** (2008) 585, [arXiv:0711.0733 [hep-ph]].
- [42] P. Q. Hung, Phys. Lett. B **649** (2007) 275, [hep-ph/0612004].
- [43] P. Q. Hung and T. Le, JHEP **1509**, 001 (2015) [JHEP **1509**, 134 (2015)] [arXiv:1501.02538 [hep-ph]].
- [44] J. Adam *et al.* [MEG Collaboration], Phys. Rev. Lett. **110**, 201801 (2013) [arXiv:1303.0754 [hep-ex]].
- [45] H. Georgi and M. Machacek, Nucl. Phys. B **262**, 463 (1985).
- [46] M. S. Chanowitz and M. Golden, Phys. Lett. B **165**, 105 (1985).

- [47] V. Hoang, P. Q. Hung and A. S. Kamat, Nucl. Phys. B **896** (2015) 611-656, [arXiv:1412.0343 [hep-ph]].
- [48] N. Cabibbo, Phys. Lett. B **72**, 333 (1978); L. Wolfenstein, Phys. Rev. D **18**, 958 (1978).
- [49] S. Chakdar, K. Ghosh, V. Hoang, P. Q. Hung and S. Nandi, arXiv:1508.07318 [hep-ph].